Practical limitations to forming carrier layers on inclined planes

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Abstract

A popular method for expanding the operability window for defect-free coating in multi-layer systems is to use a thin, low viscosity carrier layer as the bottom layer [1,2,3]. This paper examines some practical limitations on forming the carrier layer on the slide for a typical industrial slide bead coating process.

As the carrier layer flow rate is reduced to approach a critical threshold, the flow first becomes unstable resulting in broad diffuse bands on the final coating. Instability for two layers worsens with decrease in carrier layer viscosity and increase in the viscosity of the upper layer. On finally achieving the threshold carrier layer flow rate, the upper layer is seen to invade the carrier layer delivery slot. Experimental and numerical studies show that there is a critical contact angle of 65° below which the interface no longer remains stable. Flow visualisation studies demonstrate that a parallel sided slot is superior to a chamfered slot in terms of robustness against this instability. A recirculation is seen near the top of the downstream wall as the critical flow rate is approached and a mechanism for the broad diffuse bands suggested.

The results also demonstrate that the sensitivity of slide waves to pump induced disturbances rapidly grows as the critical carrier layer flow rate is approached.

1 Introduction

Limitations on line speed for the slide-bead coating process due to air entrainment and ribbing can be overcome by decreasing the viscosity of the lowest layer [1,2]. In practice, it is the viscosity measured at the shear rate typically found in the vicinity of the dynamic wetting line that matters. Hence, the lower layer may be shear thinning [3]. The wet thickness of this lower layer should exceed the substrate roughness parameter R_z [4] to be effective. This means that the layer can be quite thin when coating very smooth substrates leading to the popular concept of a thin low viscosity “carrier layer” [1].

This paper examines the cause of flow instability leading to broad diffuse bands seen on the coating in the machine direction when attempting to use a thin low viscosity carrier layer. The phenomenon is distinct from classical ribbing flow in that it originates at the exit of the bottom delivery slot instead of just upstream of the bead forming zone [2,5] – Figure 1.

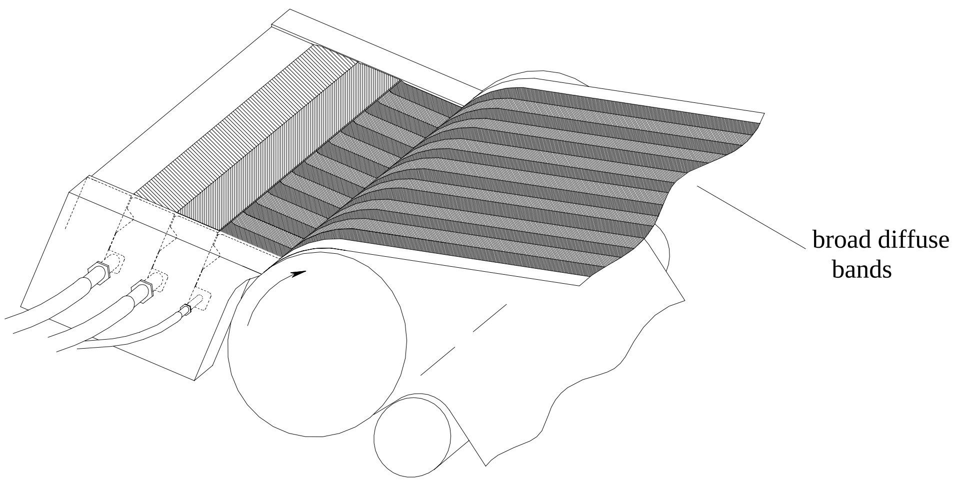

Figure 1: Appearance of broad diffuse bands associated with a thin carrier layer

The bands result from variations in thickness of the carrier layer measured in the cross-width direction. The other layers thicken where the carrier layer thins and vice versa. – Figure 2.

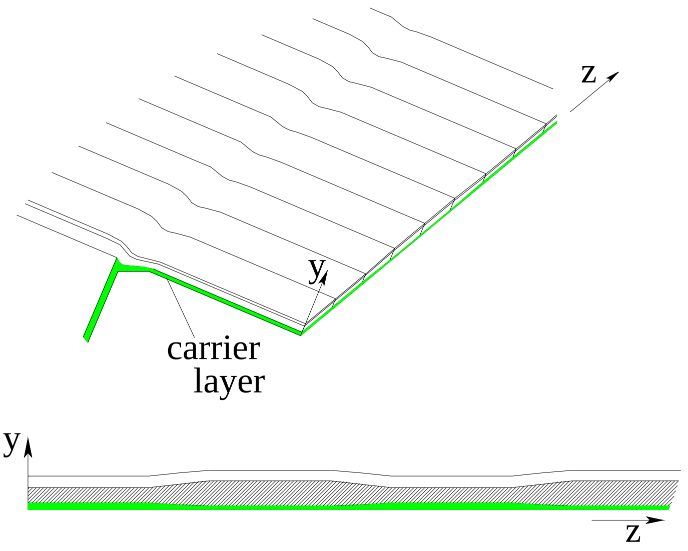

Figure 2: Typical cross-section through a three-layer flow affected by diffuse bands

2 Initial Coating Trials and Off-line Flow Visualisation Experiments

Pilot coating studies for a typical three layer coating showed that the severity of the bands worsens as the carrier layer flow rate and viscosity decrease and as the main layer viscosity increases.

A simple experiment was run using a 1.1 metre wide single slot cascade fitted with a transparent perspex back plate - Figure 3. A single slot feed was set up as shown to supply an upper layer so as to not obstruct visual access into the carrier layer slot from the back of the cascade. Adding green dye to the upper layer enabled observations on the stability of the interface at the exit of the carrier layer slot. It was seen that when the carrier layer flow rate fell below a critical value somewhat less than that causing the bands, the upper layer tended to invade the delivery slot.

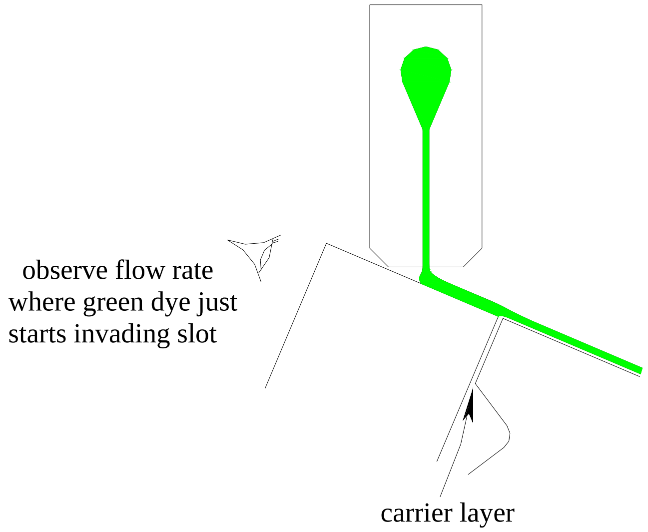

Figure 3: Apparatus for visualising the critical carrier layer flow rate

Specialised optics were accordingly developed for profiling the free surface and the interlayer interface for two layers merging at the carrier layer slot exit in order to study these effects further. The experimental set-up will now be described.

3 Experimental Set-up for Profiling the Free Surface and Interface at the Slot Exit

The method exploited the use of a narrow width transparent off-line cascade fitted with an extended slide originally designed for studying slide waves [6]. The principle behind the method involved adding a scattering agent to the upper layer while maintaining the carrier layer transparent. Silver chloro-bromide photographic emulsion prepared by a controlled crystal growth technique proved a useful additive for this work – the particle size being typically 350 nm. This enabled the profiles to be imaged using a light knife supplied from a laser beam set up to illuminate from beneath – Figure 4.

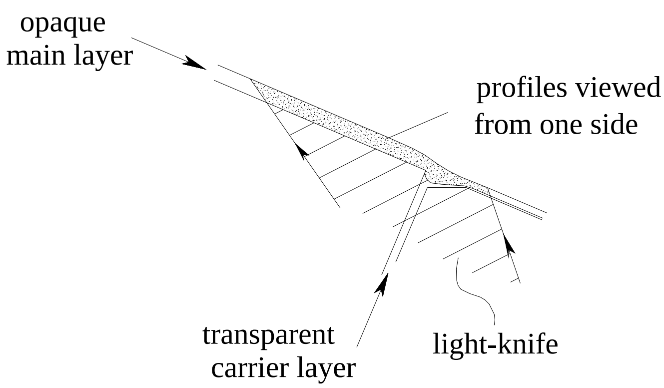

Figure 4: Principle of method for profiling free surface and interface at the slot exit

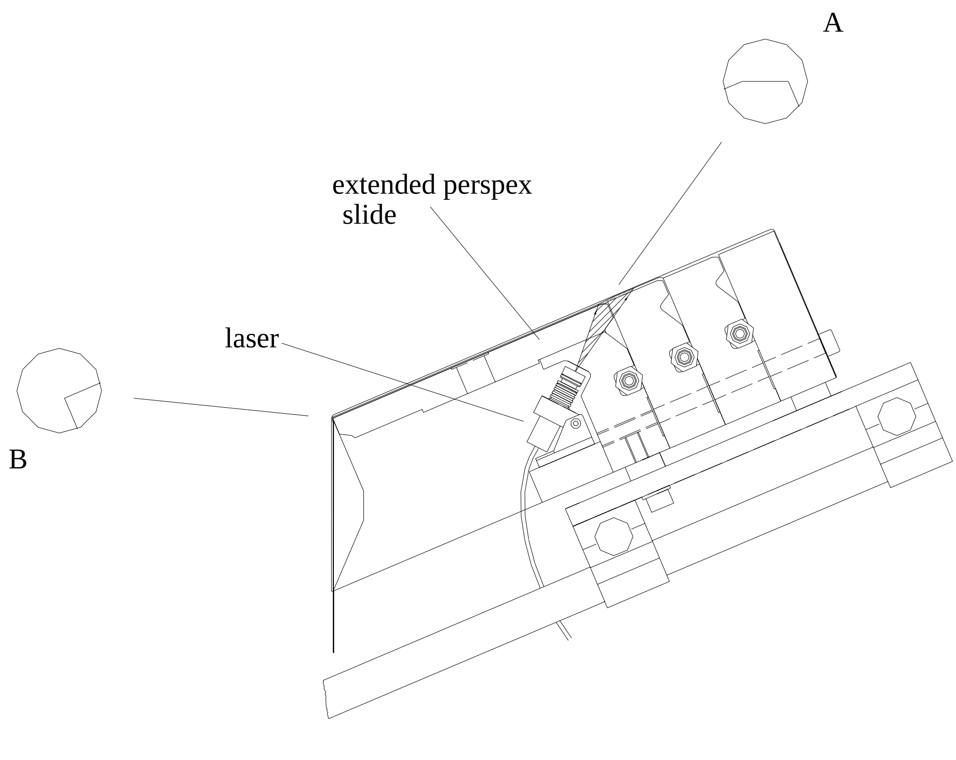

Figure 5: Perspex cascade with extended slide

The extended slide was reversible, terminating in profiles - shown “A” and “B” in Figure 5. This allowed two different slot exit geometries to be studied, one chamfered and the other having parallel walls. It was also readily possible to vary slot width over a limited range.

The recording optics incorporated a beam splitter. This allowed two directions of view, one from slightly above the edge guide for the free surface and the other declined to enable unrestricted access to the interface. A Cohu model 6712 monochrome camera fitted with Bausch and Lomb Monozoom-7E optics was used for recording the images. The camera operated at ½” format with sensitivity down to 0.005 lux and resolution 4 x 10^5 pixels. The magnification range of the monozoom assembly was between 13.4 and 93.6 and the working distance of the order of 80 mm.

PVOH of various concentrations was used as test fluid and supplied from reservoirs via gear pumps and flow meters.

4 Results

The results are presented in three parts. The first and second parts correspond to the use of a chamfered and parallel sided slot exit respectively. The chamfered slot design was originally introduced by Ade [7] to allow any slot to be used for delivering an upper layer by providing a sharp elevated upstream corner for pinning the static wetting line and thus inhibiting back wetting of the back block.

The third part discusses the sensitivity of slide waves to pump induced disturbances as the carrier layer flow rate is reduced to approach the critical value.

4.1 Chamfered Slot Exit

A CFD model [8] has been developed for flows merging at a chamfered slot exit - Figure 6. The results well match experimental profiles after assigning an experimentally determined contact angle and allowing the position of the contact line to run free [6]. The model further predicts that there is a critical contact angle of about 65°, below which it is impossible to achieve stable flow.

The results presented in Figure 7 show what happens as the flow rate of the carrier layer is reduced from 2.05 x 10^{-5} m^2/s to a critical value of 0.82 x 10^{-5} m^2/s for a chamfered slot given by CH = 1.167 mm, β = 23°, γ = 23° and B = 0.8 mm for the solution properties and upper layer flow rate given in Table 1.

	Carrier layer	Upper layer
Density (kg/m^3)	1005	1014
Viscosity (mPa.s)	5.4	74.5
Surface Tension (mN/m)	34.3	34.3
Flow rate (m^2/s)	Variable	6.15 x 10^{-5}

Table 1: Solution properties and upper layer flow rate for the chamfered slot

It will be seen from Figure 7 that the interface remains pinned to the upstream slot corner for all flows down to the critical value. The results moreover confirm that the interface becomes unstable as the contact angle θ_s falls below a value of the order of 65°.

Classical analysis of low Reynolds number flows near a static contact line (or in this case the separation streamline) predicts vortices to be generated in the stagnant wedge of fluid trapped beneath the interface when the contact angle is less than a critical value of 78° - Moffatt [9]. Noakes et al [10] showed that this was indeed the case when studying the flow at the upper slot exit of a cascade coater. A static contact angle of about 30° was found to result in excessive deposit growth at the upstream corner when continuously pumping gelatin containing a rapid hardening agent due to the recirculations trapped within the wedge of fluid. Such growths are very vulnerable to becoming dislodged and can result in coating streaks – Noakes et al [10]. In this case study, the chamfered slot exit also exposes the process to the additional risk associated with these unwanted recirculations as the carrier layer flow rate is reduced below 1.7 x 10^{-5} m^2/s and especially as the critical limit is approached.

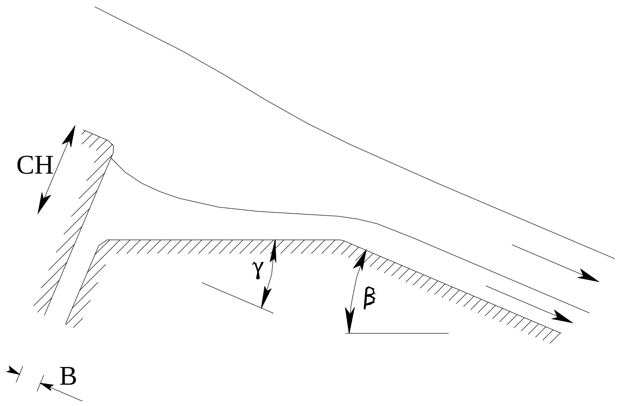

Figure 6: Merging of two layers at a chamfered slot exit

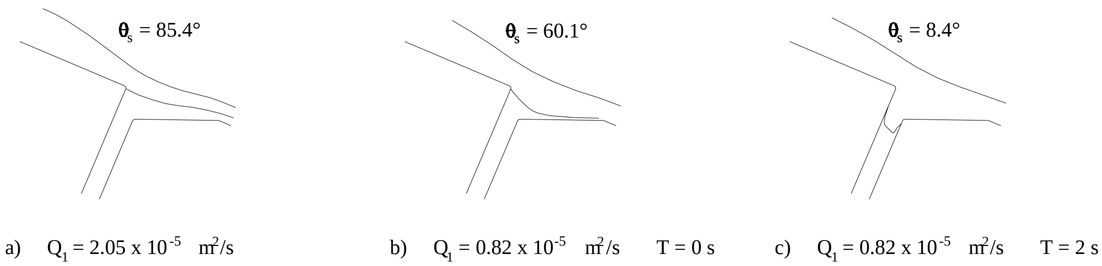

Figure 7: Effect of reducing carrier layer flow rate to critical value
Chamfered slot exit

4.2 Parallel Sided Slot Exit

It was found, using the same conditions as shown in Table 1, that the critical carrier layer flow rate decreased on replacing the chamfered slot exit with a parallel slot of the same width – see Table 2. The critical threshold further reduced on decreasing the width to 0.52 mm. The width of 0.52 mm is about the lowest practical limit owing to the impact of finite machining tolerances and pressure induced elastic distortions on the uniformity of the slot width. Figure 8 shows the profiles of the free surface and interface for the narrower parallel slot. In addition to enhancing the robustness against invasion of the upper layer, the static contact angle is also significantly increased to the order of 90° or more. This is well above Moffat's 78° limit [9] for vortices at the upstream corner.

Slot geometry	Critical flow rate (m^2/s)
Chamfered x 0.80 mm	0.82 x 10^{-5}
Parallel x 0.80 mm	0.34 x 10^{-5}
Parallel x 0.52 mm	0.07 x 10^{-5}

Table 2: Effect of slot exit geometry on critical carrier layer flow rate

Figure 8d shows evidence that the upper layer initially invades the carrier layer slot near to the downstream wall. The deformation of the apparent interface strengthens the argument put forward by Apps [8] that local mixing occurs within a vortex as predicted by the computational model – see Figure 9.

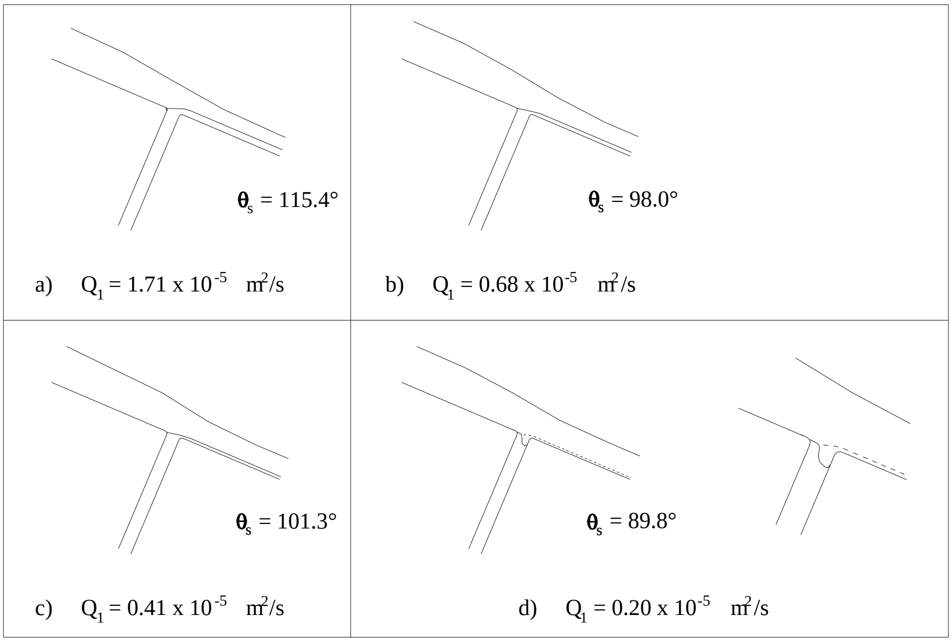

Figure 8: Experimental free surface and interfacial profiles for a 0.52 mm wide slot

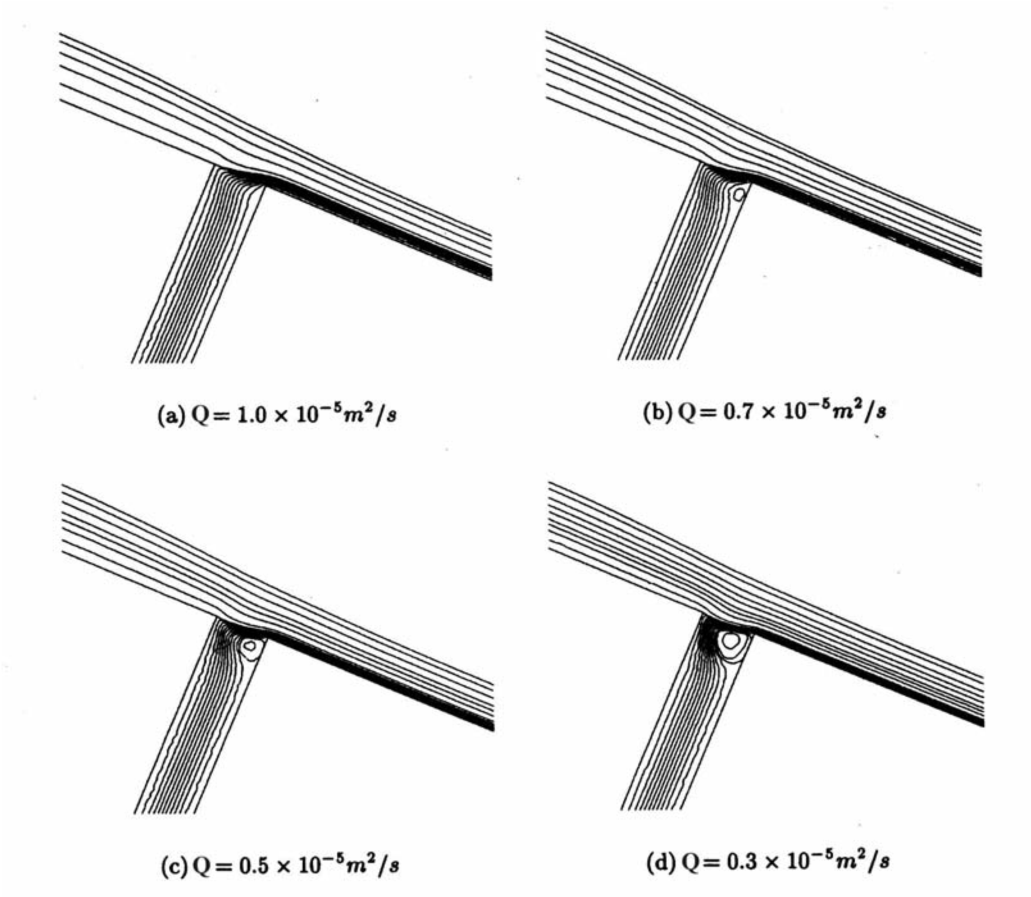

Figure 9: Flow structure for two layers as the carrier layer flow rate is reduced – Apps [7]

The results suggest a possible mechanism explaining the onset of the broad diffuse bands of varying coating weight affecting full scale multilayer coating as the carrier layer flow rate approaches the critical limit. It is initially assumed that the vortex forms a rolling bank whose strength varies periodically in the cross-machine direction – as shown in Figure 10.

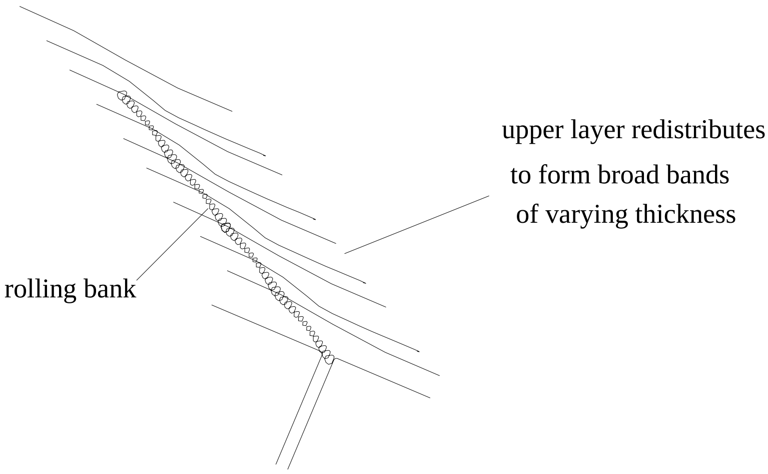

Figure 10: Possible mechanism for broad bands associated with a thin carrier layer

The vortex dissipates energy carried by the flux entering the slot exit region and results in an increased drop in pressure corresponding to the strength of the vortex. The pressure upstream of the rolling bank thus also varies between maxima and minima in the cross-machine direction. The fluid tends to flow sideways in response to local pressure gradients to augment the flux near the weak recirculations at the expense of the flux near the strong ones. The strong vortices thus grow while the weak vortices diminish. Figure 11 shows how a local weakening in carrier layer flux results is a corresponding deceleration and thickening of the main layer above. Hence the end result is a variation in thickness of both layers as depicted in Figure 1.

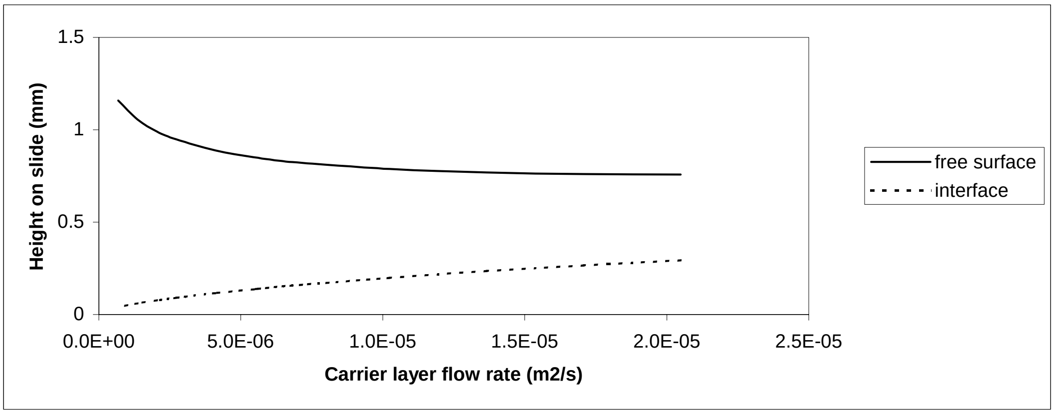

Figure 11: Effect of reducing the carrier flow rate on film thickness on the slide

The images in Figure 12 were recorded from the feed side of the coater and show what happens as the flow of the carrier layer is reduced below the critical limit. It will be seen that the upper layer begins to invade the distribution chamber supplying the bottom slot. Once this condition has been reached and the solutions become mixed within the chamber, it then becomes difficult to re-establish uniform merging flow on the slide even after restoring the carrier layer flow rate well above the critical threshold value. This is because the wall shear stress generated by the low viscosity carrier layer is insufficient to purge out the upper layer solution from the walls of the chamber. The coating operator then has no other recourse but to drain down the entire cascade, wash up and recommence the pumping up procedure. It is also evident that any transient undershooting of the carrier layer flow rate when switching set-point in a conventional control loop must be minimised in order to avoid premature failure due to layer mixing within the slot.

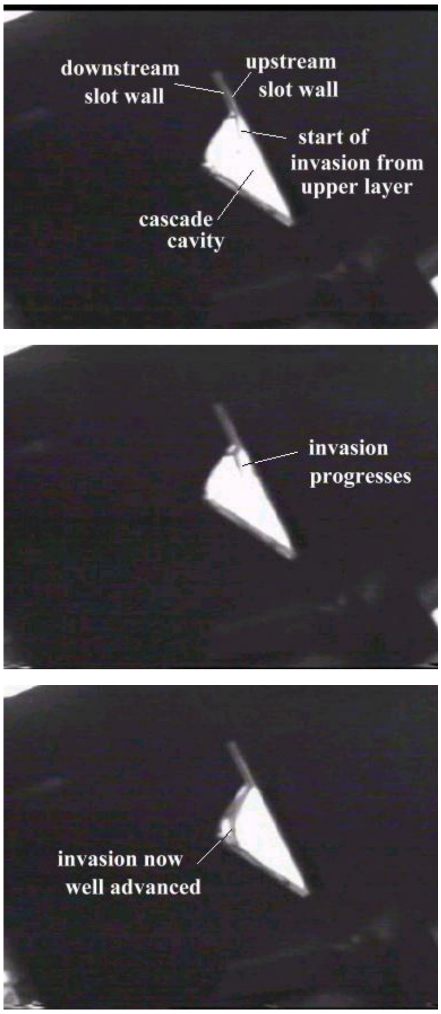

Figure 12: Invasion of the upper layer into the carrier layer distribution chamber

4.3 Sensitivity of Slide Waves to Pump Induced Perturbations

The flow on the slide downstream of the lowermost slot also became increasingly disturbed by waves as the carrier layer flow rate approached the critical threshold value – Figure 13. The temporal frequency of the waves equated to that of pulsations derived from the meshing of the gear teeth in the carrier layer delivery pump.

A second camera was set up to record the view of the slide from beneath using a folding mirror. A second folding mirror enabled a portion of the slide to be illuminated using a light box fitted with a diffusing screen. Figure14 shows how the wave amplitude rapidly increased as the carrier layer flow rate was decreased to the critical threshold of 0.56 x 10^{-5} m^2/s applicable to the conditions tested in this experiment. On reducing the flow rate further, the disturbances decreased as the upper layer thickened until a point was reached when the depth equated to that upstream of the lower slot and ceased to be influenced by the fluid hitherto forming the carrier layer.

Close inspection of the recorded images showed that the interface and free surface were oscillating up and down as the critical limit was approached. As the pressure exerted by the carrier layer pump approached a minimum, the carrier layer thinned, causing the upper layer to decelerate and thicken in accordance with Figure 11.

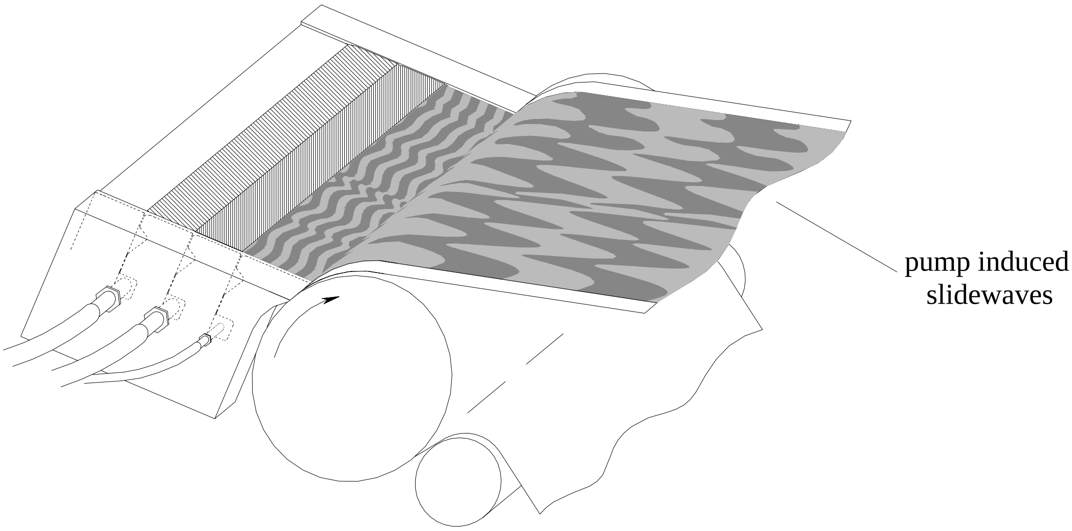

Figure 13: Illustration of pump induced slidewaves

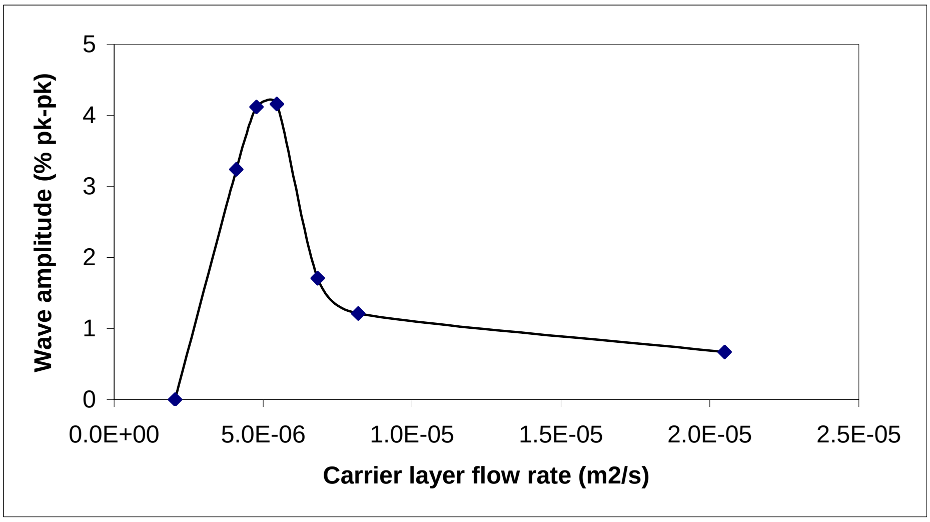

Figure 14: Wave amplitude of pump induced perturbations in upper layer thickness.

5 Conclusions

The experimental trials show there is a critical flow rate below which a carrier layer ceases to merge uniformly with an upper layer. The flow on the slide becomes unstable forming equispaced bands aligned with the edges. Pilot coating studies for a typical three layer coating show that the severity of the bands worsens as the carrier layer flow rate and viscosity decrease and as the main layer viscosity increases. On finally achieving the threshold value, the upper layer is seen to invade the carrier layer delivery slot. The experimentally determined profiles agree well with the predictions from a computational model [8], which shows that the interface remains pinned to the upstream corner provided that the contact angle exceeds 65°. The results also appear to confirm the presence of a vortex at the top of the downstream slot wall as the critical flow rate is approached. A mechanism for explaining the onset of the bands of diffuse streaks seen on an industrial scale is suggested. The design of the slot exit is important, a parallel slot being significantly more robust against carrier layer starvation effects than a chamfered slot as the flow rate is reduced. Reducing the slot width increases robustness further. The ultimate limit to width is then largely dictated by machining errors and reliability when assembling the parts forming the cascade – Ruschak et al [11]. Fine streaks arising from the upstream corner are also eliminated by the use of a parallel slot but those derived from the vortex associated with the downstream corner are unavoidable as the flow rate approaches the critical threshold value.

The experiments also show that the flow of layers merging at the lower slot becomes increasingly sensitive to perturbations in the flow rate of the carrier layer as the flux approaches the critical minimum threshold value. This is not entirely unexpected. Conroy and Weinstein [12], for example, have shown for two layer flows subjected to forced perturbations, that the interface becomes increasingly sensitive as the bottom layer wet thickness is reduced. The perturbation response reported here is nevertheless unique. This is because it is associated with the recirculation generated at the downstream slot wall as the carrier layer flow approaches starvation rather than derived from the inherent instabilities at the interface between two flows on the slide itself.

6 Acknowledgements

The authors gratefully acknowledge the financial support provided by the EPSRC through Grant reference GR/M93291/01. Thanks is also expressed to Dr. T. Rhodes of ILFORD Photo Limited for his continued support and arranging permission to use and exploit the extensive experimental facilities available within the company and for authorising the manufacture of the equipment designed specifically for this work.

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